# SONIC-POINT MODEL FOR HIGH-FREQUENCY QPOs IN NEUTRON STAR LOW-MASS X-RAY BINARIES

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Quasi-periodic brightness oscillations (QPOs) with frequencies in the range 300–1200 Hz have been detected from at least nine neutron star low-mass X-ray binaries. Here we summarize the sonic-point model for these brightness oscillations, which we present in detail elsewhere. If the sonic-point interpretation of kilohertz QPOs is confirmed, measurements of kilohertz QPO frequencies in low-mass X-ray binaries will provide new bounds on the masses and radii of neutron stars in these systems and new constraints on the equation of state of matter at high densities.

## 1 Introduction

Observations of neutron stars in low-mass X-ray binaries using the Rossi X-ray Timing Explorer have revealed that at least nine produce quasi-periodic X-ray brightness oscillations (QPOs) with frequencies $\nu_{\rm QPO}$ ranging from $\sim 300$ Hz to $\sim 1200$ Hz (see, e.g., van der Klis et al. 1996; Strohmayer et al. 1996; Berger et al. 1996; Zhang et al. 1996). These high-frequency QPOs are remarkably coherent ($\nu_{\rm QPO}/\Delta\nu_{\rm QPO}$ up to $\sim$200) and strong (rms amplitudes up to 20%). In several sources the frequencies are strongly positively correlated with countrate. In four sources, a single highly coherent QPO peak is seen during type I X-ray bursts. High-frequency QPOs have been observed to occur in pairs in six sources.

In the sonic-point model of these high-frequency QPOs, (1) the frequency of the higher frequency QPO in a pair is the Keplerian frequency at the point in the disk flow where the inward radial velocity increases steeply with decreasing radius and typically becomes supersonic, and (2) the frequency of the lower frequency QPO peak is the beat frequency between the sonic-point Keplerian frequency and the stellar spin frequency or its overtones. We emphasize that the sonic-point model is *not* a magnetospheric beat-frequency model (see Miller, Lamb, & Psaltis 1996 [hereafter MLP] for further discussion of the differences between the sonic-point model and magnetospheric models). The sonic-point model is based on earlier work on the effect of radiation forces on

disk accretion by neutron stars (Miller & Lamb 1993, 1996).

## 2 Overview of the Sonic-Point Model

The sonic-point model builds on the standard picture of the Z and atoll sources, in which the neutron star accretes gas from a low-mass companion via a geometrically thin disk and stresses within the disk create only a slow, subsonic inward radial drift. In the sonic-point model, near the neutron star there is a region of the disk flow in which the inward radial velocity increases rapidly with decreasing radius, primarily because (1) radiation from near the star removes angular momentum from the gas in the disk, allowing the gas to accelerate radially, or—if radiation forces are sufficiently weak—(2) the gas drifts inside the marginally stable orbit $R_{\rm ms}$. Because there is a sharp transition to supersonic radial inflow in a very small radial distance, we refer to this radius as the "sonic point" radius $R_{\rm sonic}$. We expect that at least some gas in the disk will penetrate in to $R_{\rm sonic}$ provided that the magnetic field of the neutron star is less than $\sim 10^{10}$ G, as in the Z and atoll sources.

We expect that the disk flow will have local density inhomogeneities, or "clumps". Because the radial velocity outside $R_{\rm sonic}$ is small, the inflow time from this region to the stellar surface is large and hence clumps produced outside $R_{\rm sonic}$ are sheared or dissipated before gas from them reaches the surface. In contrast, the inflow time for clumps from near $R_{\rm sonic}$ is small, and hence clumps formed in this region are not completely sheared or dissipated before gas from them impacts the stellar surface. The impact of gas with the stellar surface produces bright, arc-shaped footprints that move around the star. As seen at infinity, the frequency at which the pattern of arcs moves around the star is the Keplerian frequency $\nu_{\rm Ks}$ at the sonic point (see MLP). Hence, from the standpoint of a distant observer with a line of sight inclined with respect to the disk axis, the bright arcs are periodically occulted by the star at the frequency $\nu_{\rm Ks}$, and the observer sees brightness oscillations at a frequency $\nu_{\rm Ks}$. If the field is weak but not negligible, some of the accreting gas may be channeled by the magnetic field onto hot spots on the surface that rotate with the star. Because the inflow of gas from the clumps is caused by radiation drag, the enhanced radiation intensity from the hot spots modulates the mass accretion rate at the beat frequency between the sonic-point Keplerian frequency and the stellar spin frequency or its overtones. In this case, a distant observer will also see a modulation of the total luminosity at the beat frequency.

As we explain in detail in MLP, the sonic-point model explains naturally the high frequencies, amplitudes, and coherences of kilohertz QPOs and their changes with countrate, as well as the numerous other observed correlations.

The sonic-point model is also consistent with the physical picture constructed previously from observations of the spectra and low-frequency variability of the Z and atoll sources.

## 3 Predictions and Implications

The sonic-point model makes a number of testable predictions, which are discussed in detail in MLP. In particular, we do not expect kilohertz QPOs of the type discussed here in black hole sources, because in the sonic-point model the presence of a stellar surface is essential. We expect that QPOs of this type will be very weak or undetectable by current instruments from sources which show strong periodic oscillations at their stellar spin frequencies (pulsars), since these sources have strong magnetic fields and hence at most a very a small fraction of the accreting gas will reach the stellar surface without being forced by the magnetic field to corotate with the neutron star.

If the sonic-point model is correct, observation of a high-frequency QPO provides upper limits to the mass and radius of the neutron star that are independent of the equation of state and, for an assumed equation of state, yields estimates of the mass and radius of the source. These constraints can in principle rule out equations of state, particularly if high (>1300 Hz) QPO frequencies are observed, thereby constraining the properties of dense matter.

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